Approach for Evaluation of Lightning Current Distribution on Wind Turbine with Numerical Model

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Abstract—Wind turbines are increasingly becoming an important source of energy for many power systems worldwide. Reliable and safe operation of the turbines is becoming more and more important. Due to their height and exposed location wind turbines are defined as very exposed structures to lightning. A reliable lightning protection system (LPS) for wind turbines is therefore essential.

Designing the overvoltage protection system of a wind turbine the lightning current distribution and overvoltages inside the turbine needs to be analyzed. For this purpose the real structure of a specific standard wind turbine is considered. Based on the geometry and material parameters an equivalent circuit model is developed in EMTP-ATP. Using this model, the current distribution and overvoltages can simply be calculated.

In the following paper this model is used to investigate the voltage stresses occurring inside the turbine due to direct lightning strike into a rotor blade. Based on the simulation results different overvoltage concepts for the electrical and IT systems are analyzed including the investigation of the power electronic converter of a full converter wind turbine. Ultimately an overvoltage protection concept is suggested that reduces voltage stresses for the electrical and IT system as well as the power converter according to standard [1].

Keywords—Wind turbine; lightning electromagnetic pulse (LEMP); current distribution; numerical model; ATP/EMTP; overvoltage protection (OVP); variable-speed wind turbine; power electronic converter

I. INTRODUCTION

Within the last decade wind power has expanded rapidly. Over 51 GW of wind power was installed in 2014, accounting for over 17% of net additions to the world capacity in the power sector and reaching a global total of 370 GW [2]. Due to innovations and technological development wind turbines (WT) increases both in size and rated power output. Nowadays power ratings ranges from 2 MW to 4 MW with rotor radii between 90 m and 150 m and total heights of up to 200 m.

The WTs are frequently built in open unshielded areas, along mountain ridges and on hill tops. Due to their height and location, they present very exposed structures to lightning. According to an extensive study conducted together with Lightning Detection Network BLIDS, the WTs in Central Europe are hit many times throughout their operating time with currents of up to 200 kA and above. The lightning currents are conducted via the rotor blade (RB) into the nacelle and from there along the tower into the earth-termination system. Due to their high amplitudes and steepness, they cause extremely high potential differences inside the turbine.

Mitigating dangerous potential differences inside the WT surge arresters are installed in order to protect both electrical and IT system. The international wind turbine protection guide line IEC 61400-24 does provide indications for the placement of surge protection devices (SPDs) inside the turbine referring to the Lightning Protection Zone Concept (LPZ). Applying the LPZ concept for WTs however is not straight forward and causes challenges since it is not clear how the lightning current flows from the blade into the earth-termination system. The lightning current distribution inside the WT is therefore investigated using EMTP-ATP. In a first step an equivalent circuit is derived for a specific WT including the relevant WT components such as the RB, nacelle, tower earth-termination system and the electrical and IT system as lumped and distributed elements. Secondly, an electrical circuit of the entire WT is developed based on these impedance models. Then first positive stroke and subsequent stroke currents are injected into the model. The resulting overvoltages are investigated both with and without SPDs. By varying the location of SPDs optimal positioning can be evaluated.

II. NUMERICAL MODEL

For the investigation a standard multi-megawatt WT with horizontal axis and 3 RBs was chosen. The rated power of the WT is 2.4 MW with a hub height of 141 m and a rotor diameter of 117 m. The schematic view of the turbine is shown in Fig. 1. The operating voltage of the generator is 0.69 kV. The power is adjusted by a full power converter according to the grid compliance of the system operator. The grid connection is then realized by a transformer which steps the voltage up to 20 kV. For further designing of numerical network model in EMTP-ATP [3], [4], all components of WT are described in more details below.

A. Rotor blade

The metallic conductors inside of the blades are used for diverting the lightning from the tip and surface of the blades thereby avoiding the formation of destruction of the RB.
For initial investigation, the model with surge impedance $Z_{RB}$ can be used for modeling of RB [5], which is calculated analogous to an overhead line (horizontal position of RB is assumed) with its height $h_l$ (in our case is height of the hub, $h_l = 141$ m) above ground and its down-conductor radius $r$ (according to 25 mm²). The RBs are modelled as a single-phase system with “LINEZT_1” component in EMTP-ATP. The component is represented by surge impedance $Z_{RB}$ and can be found as follows:

$$Z_{RB} = 60 \ln \left( \frac{2h_l}{r} \right) (1)$$

The consideration of all three RBs (not coupled by field between each other) is important for accurate estimation of reflection behavior at hub. The length of RB is 58 m. The estimated in this case surge impedance $Z_{RB}$ equals 690 Ω.

**B. Tower**

The tower of WT has been represented in EMTP-ATP by a LCC component (Line/Cable Constants) with Bergeron line model with average radius of tower $r_n$. The actual tower body is represented by a pipe ("enclosing pipe") with a poor conductivity (representing reinforced concrete with $\sigma = 7.7\cdot10^6$ S/m) and with an equivalent radius $r_n = 4.4$ m. To avoid the connection of pipe to the earth potential, which is in default in EMTP-ATP for LCC component, an external tap to the pipe was generated by increasing the number of phases. It should be set by one more as the number of cables inside. The relative permeability $\mu_r$ of tower’s body is set by 200 for steel and the thickness of pipe wall is assumed to be 20 cm in middle. One advantage using EMTP-ATP is that all coupled parameters such as mutual inductances and capacitances inside the tower between the cables and the tower, between the cables themselves etc. are evaluated by the program by itself. The LCC component can be set for only one certain value of frequency per one calculation cycle. To be able to represent an impact of impulse currents, certain equivalent frequencies $f_c$ were chosen under assumption that the highest impact is located namely at the front of the impulse current (because of the inductive effect). In this case each impulse wave shape can be represented by its equivalent frequency $f_c$: $10/350 \mu$s with 25 kHz and $0.25/100 \mu$s correspondingly with 1 MHz. In the observation the frequency 50 Hz is also included. Some calculated total electrical parameters of the LCC component due to EMTP-ATP for different values of frequency are summarized in Table I.

![Schematic view of investigated wind turbine configuration](image)

**Figure 1.** Schematic view of investigated wind turbine configuration: (1) down-conductor, (2) generator, (3),(6) control cabinet, (4) power cable system, (5) dataline and power supply line, (7) inverter module, (8) power transformer 20 kV/690 V

The evaluated values with the formulas show a good agreement with the designed network model in EMTP-ATP at low frequency. It should be underlined again that the model of the tower has a horizontal position to earth’s surface in EMTP-ATP representation.

**C. Power cable system**

The electrical power from the generator to the bottom of the tower is transferred via a low voltage cable system (EL) comprising in our model 6 NYY 1x 400 mm² cables. The cables are inlaid in the tower corresponding to the Fig 2. A protective earth cable (PE conductor) which is connecting the equipotential bonding bar in the nacelle and tower bottom is inlaid in the tower as well. All considered cables covered with insulation with $\varepsilon_i = 2.4$ and conductor’s material is copper. The cables have no shield. The information about location and geometry of the cables is presented in the Table II.

**Table I.** Evaluated with LCC component electrical parameters for the tower

<table>
<thead>
<tr>
<th>Calculated parameters</th>
<th>EMTP-ATP</th>
<th>Hand formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>$50$ kHz</td>
<td>$76$</td>
<td>$70$</td>
</tr>
<tr>
<td>$25$ kHz</td>
<td>$76$</td>
<td>$70$</td>
</tr>
<tr>
<td>$1$ MHz</td>
<td>$9.66$</td>
<td>$7.6$</td>
</tr>
<tr>
<td>Characteristic</td>
<td>$202$</td>
<td>$153$</td>
</tr>
</tbody>
</table>

**Table II.** Parameters of cable systems

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_i$, $R_i$, $\varphi$</td>
<td>Radius of inner conductors, outside radius of cables of power network and angle between adjacent cables including PE</td>
<td>$r_i = 12$ mm, $R_i = 17$ mm, $\varphi = 7^\circ$</td>
</tr>
</tbody>
</table>
D. Earth-termination system

The earth-termination system (ETS) which is integrated into the footing is made out of a steel structure. The ETS is sufficiently represented by an equivalent circuit model represented by $L_{ETS}$, $R_{ETS}$ and $C_{ETS}$ which was successfully proved with GSA FD (Grounding Systems Analysis in the Frequency Domain from SINT Ingegneria, Italy) in case of specific soil resistivity $\rho_s < 500 \Omega\cdot m$. The model is frequency dependent.

E. Power electronic module

Finally, an equivalent circuit for the power converter was developed. The power converter for initial investigation was modeled only for one switching position. This is plausible because time periods of only a few 10 $\mu$s are investigated for lightning events while the switching time takes over 30 $\mu$s. The circuit of the power converter and the corresponding switching positions are displayed in Fig. 7. Further the overvoltages, which are appearing at the heat sink, at the intermediate circuit capacitors (ICC) or at the IGBTs, will be investigated with designed model.

III. SIMULATION RESULTS

The numerical simulation model for the study of lightning current distribution and overvoltages due to direct lightning strikes was designed for a specific WT in EMTP-ATP. The schematic view of the model is shown in Fig. 3. The following investigations are conducted for two cases: 1) without OVP, 2) with OVP. Thereby both first positive stroke 10/350 $\mu$s with a peak value of 200 kA (FPS) and negative subsequent stroke 0.25/100 $\mu$s with an peak value of 50 kA (NSS) are considered [9].
and IT systems and the earth-termination system. It noticeably exceeds the insulation strength of the inverter components (e.g. IGBT has 4 kV) and the insulation of the transformer. The voltage drop along the earth-termination system (EARTH) is 2 MV for NSS and 1 MV for FPS. In the considered case, the neutral point of the transformer is connected to the ETS of the tower (Fig. 3).

In a second step the current distribution along solid components and the cable system inside the WT is examined. The results of the EMTP-ATP simulations are depicted in Table IV, especially the maximum current peak values for different components of the WT in case of both NSS and FPS. As it has already been shown in our previous paper [10], reflection effects occur along the lightning current path from the RB to the earth-termination system. The numerical model takes the effect of current wave reflection into account. The reflection occurs when there is an impedance change along the currents path. At the designed network model the reflections mainly takes place between the boundary of RB (M_ROT) and the tower and the boundary of the tower and the earth-termination system (EARTH). The reflection between RB and the lightning channel is not considered within this study.

In our model the characteristic impedance of the RB ($Z_0$) is greater than the characteristic impedance of the tower ($Z_t$) which leads to a positive current reflection coefficient $\Gamma_t$ at this boundary. Therefore the impulse current peak is about 30 % higher than the injected current at the top of the tower. Looking at the tower foot the resistance of ETS is much lower (10 Ω) than the characteristic impedance of the tower $Z_t$. That means the reflection coefficient is also positive and much higher. As a result, the amplitude arises by another 75 % at the tower bottom. In total the current rises by approximately 128 % and therefore doubles. A similar observation during real lightning current measurements at the 634 m broadcasting tower Tokyo Skytree have been done and it is described in more detail with a corresponding electromagnetic model in [11]. The current distribution along the lightning current’s main path is depicted in Fig. 5 showing the currents inside the RB, tower and earth-termination system. The reflection effects are clearly seen for NSS looking at Fig. 5 a). As shown the current increases going from RB to tower and from tower to the earth-termination system. However, for FPS in Fig. 5 b) only slight reflections are observed. The corresponding maximum values are summarized in Table IV.

![Figure 4. Reflection in wind turbine during flowing of step current 100 kA](image)

The estimated current reflection coefficient at the tower top $\Gamma_t$ with a step function of current (SF) is around 0.3 for case with three RBs (Fig. 4). Looking at the tower foot the current reflection coefficient $\Gamma_d$ with low ground resistance (10 Ω) reaches around 0.75. The formula for estimation of incoming maximum impulse current to the ETS in this case can be expressed as follows:

$$i_{t,1MHz} = \hat{i}_L \cdot (\Gamma_1+1) \cdot (\Gamma_2+1)$$

(1)

where $\hat{i}_L$ is peak value of injected lightning current. In case of NSS the peak value of 50 kA at the RB tip turns into a maximum value of around 113 kA at the ETS when only one RB is considered. Looking at the model in Fig. 3 with three RBs the reflection coefficient at the tower top $\Gamma_t$ is approximately 43 % smaller if the other two RBs are taken into account. That is because each model for RB considers distributed capacitance to earth which is especially noticeable during very steep lightning current impulses.

![Figure 5. Lightning current reflection at different boundaries of wind turbine during flowing of a) NSS and of b) FPS](image)

**B. Case with OVP**

As shown the direct lightning strikes cause extremely high overvoltage inside the WT. Enabling a reliable and safe operation of WT’s therefore requires the implementation of an overvoltage protection system (OVP) to limit overvoltages to levels which do not damage or cause operation errors to the electrical and IT system. Looking at the previous simulations extremely high overvoltages occur between the power electronic system and IT system including its cables and the earth (EARTH) or local earth (PE_LOC) with regard to the nacelle since they have no galvanic connection to the local potential of its surroundings (Fig. 3). The lightning strikes cause extremely high potential rises and ultimately flashover if OVP is not applied.
Therefore a functioning OVP system is crucial for safe and reliable operation of WTs. However, until now it is not fully clear how to design the OVP of WTs. Designing an OVP system the following criteria should be considered: a) all differential overvoltages (e.g. between plus und minus of power supply), as well as b) the overvoltages applied between conductive parts and earth which coming from outside or caused inside of the power electronic system, c) all isolated conductive parts (such as heat sink of IGBTs), and d) shape of voltage by periodic switching in converter in case if metal oxide varistors (MOV) are used. Preventing overvoltages inside the considered WT the OVP in Fig. 6 is investigated. The SPDs are installed both in the nacelle and the tower foot.

Looking at the OVP concept the SPDs are installed inside the nacelle between the electrical and IT system and the local earth (PE_LOC). At the tower foot they are installed between the electrical and IT system and the earth-termination system (EARTH). Furthermore, a simple realization of the internal OVP concept of the voltage source inverter (VSI) is demonstrated on single-phase VSI which is basic component of power electronic system shown in Fig. 7 [12]. Two SPDs (in our case two spark gaps or SGa and SGb) between heat sink of IGBT and positive and negative terminals of ICC are required to prohibit arise of dangerous voltages. Usually neutral N is used for preventing of an oscillating current i_N which flows through neutral and can be controlled via a damping resistance R_D of some ohms. Thereby, because of EMC reasons [13] the neutral cannot be considered as a place for installation of SGs. In its turn, the IGBT heat sink can be connected to the local earth via additional SGc as well. In both cases the elimination of strong potential rise will be achieved.

For initial investigation the SGs are used for protection of power and information cable systems as well as for power electronic inverter. Protection levels of SG for EL system of 2.5 kV and for IT system of 1 kV are chosen. Three following OVP concepts are investigated: I) SGs are installed at ICC according to Fig. 7, II) SGs are installed at the tower foot for both IT and EL systems additionally and III) SGs are installed at the tower top for IT and EL systems as well.

1) OVP Concept I

The SGs are installed at the ICC according to Fig. 7. This equalizes the overvoltage between heat sink and incoming and outgoing power lines of power electronic system. The resulting overvoltages inside the WT for this OVP concept are displayed in Fig. 8 and Fig. 9. Namely the OVP concept I considerably reduces the overvoltage from several MVs to in maximum of 20 kV at the heat sink. This voltage value is higher than the set protection level of SGs (2.5 kV).

Additional voltage drop comes from the terminals of installed SGs which the model takes into account. The overvoltage also was reduced at the low voltage side of transformer (Fig. 8 a) from several MVs to 5 kV. However, overvoltages in the EL system at both the tower foot and tower top (Fig. 8 b) and c) are not eliminated. The overvoltages at the tower top are measured against local earth (PE_LOC) and at the tower foot against ETS (EARTH). Instead of SG1 and SG2 metal oxide varistors (MOV) can be used. The selection procedure for appropriate MOVs in VSI is described in [14].
2) OVP Concept II.

Additional SGs are installed at tower foot for EL and IT systems with corresponding protection levels and are connected to the ETS (Fig. 6). Conducting the simulations for this model additional reduction of the incoming overvoltages at ICC as well as at low side of the transformer (Fig. 8 a) is observed. Furthermore, reductions of potential differences in EL system at entrance of power electronic system are achieved (Fig. 8 b). Also a positive effect can be seen in the IT system at the tower foot (Fig. 9 a). Here the overvoltages are reduced to the protection level of SGs. However, the applied OVP concept does not reduce the overvoltages in both EL and IT systems in the nacelle (Fig. 8 c, Fig. 9 b). Concluding the additional installations of SGs at the tower foot is not sufficient to reduce the overvoltages inside the entire WT. Therefore further actions are necessary.

3) OVP Concept III.

The OVP concept III furthermore includes the installation of SGs in EL and in IT systems inside the nacelle (Fig. 6). The SGs in the simulation model at the tower top are connected to the local earth (PE LOC). The simulation results for this OVP concept III are shown in Fig. 8 c for the EL system and for the IT system in Fig. 9 c respectively. As it can be seen the overvoltages are reduced to uncritical values. Therefore this concept is able to handle all overvoltages inside the entire WT with regard to both EL and IT system in the nacelle and the tower foot and in the VSI. In Table III the results of the simulations are summarized showing that all identified overvoltages are eliminated with OVP concept III. Looking at the results some voltage values are above the specified protection levels of SGs (2.5 kV for EL or 1 kV for IT systems). They are caused by the inductance of the SG connection cables (terminals) due to the flow of high steepness currents.

<table>
<thead>
<tr>
<th>Node</th>
<th>Description</th>
<th>Without OVP, MV</th>
<th>With OVP conc. III, kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>EL1</td>
<td>Power cable at the generator output / tower top / against local earth (PE LOC)</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>IT1</td>
<td>IT cable / tower top / against PE LOC</td>
<td>4.5</td>
<td>2.2</td>
</tr>
<tr>
<td>EL2</td>
<td>Power cable / tower foot / against earth (EARTH)</td>
<td>2.2</td>
<td>2.5</td>
</tr>
<tr>
<td>IT2</td>
<td>IT cable / tower foot / against EARTH</td>
<td>3.5</td>
<td>1.7</td>
</tr>
<tr>
<td>Uicc1 &amp; 2</td>
<td>Positive / negative terminals of ICC / against EARTH</td>
<td>2.2</td>
<td>9.1</td>
</tr>
<tr>
<td>U_tr1</td>
<td>Transformer input / against EARTH</td>
<td>-2</td>
<td>9.1</td>
</tr>
</tbody>
</table>

With regard to the OVP concept III the specific energy \( W/R \) for each SG was calculated. The maximum values for NSS and FPS are listed in Table V. According to the results the SGs installed in the IT system and inside the VSI are exposed to the highest stress (up to 20 kJ/Ω in case of NSS). With regard to FPS the value of the specific energy of SGs installed at VSI reaches up to 520 kJ/Ω. However, the calculated values represent the results for the equivalent electrical circuit of the WT shown in Fig. 6 being comprised of only one rectifier and inverter. In reality, however, several power rectifiers and inverters are connected in parallel. As a result, if each power module has its own OVP system on the basis of MOVs several SG configurations are installed in parallel. They all conduct approximately the same currents. Therefore in real WT the values of impulse currents and specific energies are actually much lower.

As conclusion the overvoltages due to direct lightning strikes are reduced sufficiently applying the OVP concept III. However, as a side effect to the protection system considerable
lightning current can flow through IT cables (Table IV, especially during FPS) for short periods of time.

**TABLE IV. CALCULATED PEAK CURRENT VALUES**

<table>
<thead>
<tr>
<th>Description</th>
<th>Without OVP, kA</th>
<th>With OVP conc. III, kA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SF 1 RB</td>
<td>SF 3 RB</td>
</tr>
<tr>
<td>Injected current (i_t)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Pos.1 (ROT_M)</td>
<td>170</td>
<td>130</td>
</tr>
<tr>
<td>Pos.2 (EARTH)</td>
<td>305</td>
<td>228</td>
</tr>
<tr>
<td>IT cable / tower top</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IT cable / tower foot</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EL cable / tower top</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EL cable / tower foot</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PE conductor / tower foot</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

For further reduction of the current the second stage of surge arresters may be needed applying the lightning protection zone concept and introducing LPZ 2.

**TABLE V. CALCULATED MAXIMUM VALUES OF SPECIFIC ENERGY FOR SGs FOR OVP CONCEPT III (kJ/kA)**

<table>
<thead>
<tr>
<th>Cond.</th>
<th>VSI</th>
<th>EL foot</th>
<th>IT foot</th>
<th>EL top</th>
<th>IT top</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSS</td>
<td>18.6</td>
<td>2</td>
<td>19</td>
<td>1.64</td>
<td>18.7</td>
</tr>
<tr>
<td>FPS</td>
<td>520</td>
<td>62</td>
<td>246</td>
<td>237</td>
<td>240</td>
</tr>
</tbody>
</table>

**IV. DISCUSSION**

The proposed initial internal OVP concept, demonstrated in Fig. 6, has following functions: (1) OVP for entire EL and IT systems, (2) defining of the electric potential at the isolated parts which allows avoiding strong potential rise at these parts. Besides that, the concept should not affect the functionality of power electronic system.

The selection procedure of surge protection devices for such power electronic network components is already discussed in details in [14]. The first simulation on VSI with impulse current 8/20 μs of 25 kA is already done and also described in [14].

The presented simulation results reveal the importance of taking into the consideration of current wave reflections which could occur at the WT during the flow of lightning impulse currents. (The travelling wave’s effect in WTs becomes significant as their physical dimensions are increased.) The presented numerical model in EMTP-ATP can successfully represent this effect. Nevertheless, the obtained results are still going to be verified with measurements due to several installed Rogowski coils on real WT. The final validated network model is planned to be used for further analyzing of LEMP environment inside of the WT on the basis of the current distribution via, for example, FEM calculations.

In future the investigation with different set-ups for cable laying (in the middle or close to the wall of tower) is planned. Also the high-frequency components which are appearing during the normal switching operations of power electronics components can influence the properties of installed SGs (already considered in [14]).

Recently it was reported about “initial continuing current only” (ICCOnly) type of upward lightning discharges [15]. These continuous current have no impulses and are difficult to detect although they could have a high charge transfer (783 A as reported in [15]). For WT a large transferred charge could be a more critical parameter (e.g. for RBs) as the peak value of lightning currents observed here. Further investigation with network model and continuous current is planned.

**V. CONCLUSION**

The numerical network circuit for the study of lightning current distribution for a specific WT was designed by means of the network simulation program EMTP-ATP. The obtained results show that dangerous overvoltages appear in power (EL) and in information (IT) cable systems and in power electronic system during lightning current flow. In general two lightning impulse forms are considered: 1) subsequent current impulse (NSS) 0.25/100 μs, 50 kA and 2) first positive current impulse (FPS) 10/350 μs, 200 kA. The first impulse current waveform (NSS) allows investigating maximum values of induced voltages because of high current steepness and the second (FPS) of the maximum energy stress.

For the first investigation overvoltages in both EL and in IT system as well as the power converter and transformer were analyzed using the numerical EMTP-ATP model without consideration of any overvoltage protection (OVP) concept.

The final presented version of OVP concept for considered WT has been obtained incrementally. First the OVP was considered for power electronic system only to avoid a potential rise at insulated parts since heat sink of the inverters themselves have no connection to the ground. Sufficient reduction of overvoltages at all components of power converter was achieved, however, dangerous voltages still occurred in the tower foot and nacelle. Therefore the OVP was extended by SGs inside the tower foot. This lead to significant reduction of overvoltages in the tower foot. However, there was still no influence to the critical potential rises in the nacelle.

Therefore, in a third step, surge protective devices were also installed in the nacelle for EL and IT systems. The final version of OVP concept showed satisfactory results with respect to dangerous overvoltages, although resulting in relatively high values of impulse currents in the IT system. In a second stage further surge arresters may be needed for further reduction of current values here. Thus, the numerical model shows that installation of overvoltage protection devices at both sides of IT and EL systems: at the top and bottom of the tower are required.

It was also emphasized that the reflections of lightning current waves at the boundaries between RB and the tower as well as between the tower and the earth-termination system.
can cause a significant increase of lightning current peak values at the bottom of the tower. Further developing and improving of the designed network model is planned as well as measurements at a real WT for calibration purposes. With help of additional tools (FEM) the obtained lightning current distribution can be used for representation of LEMP environment inside of the WT.

REFERENCES